# Iso Efficiency Contours as a Concept to Characterize Variable Speed Drive Efficiency

W. Deprez, J. Lemmens, D. Vanhooydonck, W. Symens, K. Stockman, S. Dereyne, J. Driesen

*Abstract* -- **Despite recent revisions and harmonization efforts of international motor efficiency standards which has lead to the revised IEC Std 60034-2-1 and the efficiency classification of IEC Std 60034-30, there remains a lacuna in the context of motor systems efficiency. Although IEC is preparing a "Guide for the selection and application of energy-efficient motors including variable-speed applications" labeled IEC Std 60034-31, to date, there is no internationally accepted test protocol that allows the determination of drive system efficiency at different load points. As the first in a set of three by a joint research project of three research institutes, this paper introduces iso efficiency contours as a useful tool in this context. The concept of these contours as well as their mutual interaction with system specifications and losses are discussed. A first testing protocol for all types of motor drives is proposed. The concept is illustrated by first results of an extensive testing campaign.**

*Index Terms* -- **Variable Speed Drives, Efficiency, Standards, Iso Efficiency Contours, Motor Drives, Motor Losses**

## I. Introduction

The importance of electric motor driven systems in industrial applications and especially their share in electricity consumption is well documented and accepted. Approximately 65% of the electricity which is used in industry is consumed by electric motors, the majority (90%) of the industrial motors being induction machines. This explains the vast amount of initiatives and standardization efforts in the context of energy efficiency of induction motors over the past decade [1-3]. Some of the most important achievements in this context are the increased awareness for the opportunities and importance of energy efficiency in motor driven systems, and the publication of the revised IEC Std. 60034-2-1 and of the new IEC Std. 60034-30 concerning the "Methods for determining losses and efficiency from tests (excluding machines for traction vehicles)" and "Efficiency classes of single-speed, three-phase, cage-IMs (IE-code)" respectively [4, 5].

The rising market penetration of variable (or adjustable) speed drives (VSDs or ASDs) contributes to the increasing awareness of their potential in terms of energy savings in motor systems, but also in terms of technical solutions. Many modern applications require accurate control of speed and even torque, which can be facilitated by the use of power electronic converters. Moreover, other motor types such as permanent magnet synchronous motors or switched reluctance motors inherently operated with power electronic converters are increasingly filling up niches in the market. They are even becoming economic alternatives for induction motors in VSDs.

To date, there is no internationally accepted test protocol that allows the determination of drive system efficiency at different load points. However, for proper design, measurement and assessment of the energy performance of drive systems, the classic motor efficiency standards cannot be used as they are designed for direct-on-line applications. Several international initiatives try to fill this lacuna. For instance, the new IE4 efficiency limits [5] are formulated for an entire torque-speed range. Additionally, IEC is working on a new draft standard for the determination of efficiency of VSDs [6].

There are three main issues concerning the assessment, design and choice of VSD system components when it concerns their energy efficiency. Firstly, there is the problem of the determination of the efficiency for different load points. Compared with direct-on-line efficiency, there are much more possible operating points and the method of loss segregation as it is installed in most efficiency determination standards is not readily applicable. Secondly, the nature of VSDs makes that there are multiple 'degrees of freedom' that influence the systems efficiency. In fact, there is a mutual influence of motor, converter, control algorithm and parameter settings on the respective losses in motor and converter. And thirdly, there is no harmonized system for the visualization or classification of the VSD efficiency over the entire operating range yet. However, in the context of (electrical) drive trains for vehicles a useful concept is already in use for years, namely the so-called efficiency maps or iso efficiency contours [7]. They are in fact the loci of equal efficiency values plotted as function of speed and torque as abscissa and ordinate respectively (e.g. Fig. 5). In that "vehicle context" they are proven to be useful for characterization and design of power trains. This concept was adopted for preliminary experiments with induction motor drives and introduced to industrial partners which welcomed this concept enthusiastically for up till now they had to satisfy with direct-on-line efficiency data and make further assumptions what converter influence is concerned. If such efficiency maps would be readily available for motor/converter combinations, it would be an enormous advantage for machine manufacturers when it comes to drive selection as their applications' load trajectories can be linked to the efficiency contours.

In this paper, a research project initiated by three collaborating research institutes focusing on this opportunity and lacuna in motor efficiency standardization is introduced. First the parameters and variables affecting VSD losses are briefly treated. Next, iso efficiency contours are introduced. Then, general prerequisites to enhance accuracy and reproducibility of efficiency measurements are summarized. This includes the description of a test-bench and -procedure.

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Finally, an interesting example based on experimental data is given.

## II. Efficiency of VSD Systems, a Multi-Variable Approach

In this section, VSD efficiency is elaborated more in detail for an induction motor type in order to gain insight in system losses and the main influencing factors. A similar analysis can be made for other motor types in VSD applications.

### A. *Direct-on-line versus Inverter-fed losses*

In comparison with direct-on line connection, the analysis of inverter-fed induction motor losses and efficiency determination is more complex and requires a different approach. In case of direct-on-line connection, the voltage and frequency are imposed by the power supply leading to a certain torque-speed characteristic. The operating point on this curve is only a function of load torque yielding a certain slip value. For given material properties and geometry, the main motor losses under reference conditions are determined by the flux and slip values at this operating point. Hence, for a given motor each torque-speed combination over the entire operating range corresponds with a unique distribution and magnitude of losses allowing a reproducible determination of efficiency according to the standards [4, 5, 8].

This is not the case for inverter-fed induction motors which have numerous influencing factors that are system-dependent. In a certain operating point the flux, slip, fundamental frequency and switching frequency are degrees of freedom depending on the inverter and control algorithm. A variation in these degrees of freedom will not only affect the magnitude and distribution of losses in the motor, but also in the inverter. Each combination of motor, inverter and control algorithm represents in fact a multi-variable system causing the conditions for efficiency determination in each system to be different. Hence, an objective comparison between VSD systems for a given application based on manufacturers efficiency data is not feasible. As stated in the introduction, efficiency contours of VSD systems (motor, converter and control algorithm combination) provide a useful tool for comparison.

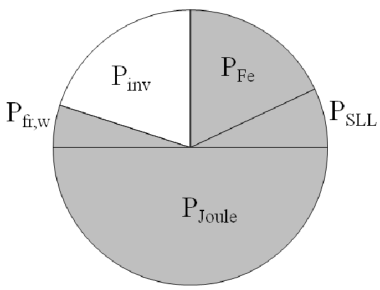


Fig. 1. Example of a typical loss distribution at the nominal operating point of a 11 kW 4 pole IE2 induction motor and inverter (96% efficiency) [6].

In order to analyze, interpret and compare efficiency contours, knowledge of the origin of the different loss components (Fig. 1) and how they are influenced by inverter parameters is essential. The following paragraphs give a brief overview of losses in an inverter-fed induction motor system and point out the main correlations between losses and electrical quantities imposed by the inverter (Table I).

### B. *Inverter and Motor Loss Components*

The inverter losses $P_{inv}$ subdivide into two major portions; conduction losses $P_{cond}$ and switching losses $P_{switch}$. Others (e.a. blocking and driver losses) can be neglected [9]. The conduction loss is a product of inverter output current and a fixed voltage drop across the transistors and diodes. When the switching elements (usually IGBT’s) change states, the current through and the voltage across the switch does not change instantly. The product of voltage and current during each transition represents a switching loss, proportional to the switching frequency.

Induction motor losses can be subdivided in order of descending magnitude [10]:

-Joule losses $P_{Joule}$ in stator windings and rotor bars are proportional to the resistances and the currents squared.

-Iron losses $P_{Fe}$ (hysteresis and eddy-current losses) augment approximately with fundamental frequency and flux level squared. More harmonic content in the motor current yields small fast changes in flux level and minor additional hysteresis loops causing respectively more eddy-current and hysteresis loss.

-Friction and windage losses $P_{fr,w}$ depend on motor speed.

-Stray load losses $P_{SLL}$ (additional losses) are due to time and space harmonics and leakage flux caused by magnetic saturation, practical slot geometry and supply distortions. They increase with load current and harmonic content.

TABLE I
Correlations Between Inverter Output Variables and Loss Components in a VSD Induction Motor.

| | Inverter | | Motor | | | |
|---|---|---|---|---|---|---|
| | $P_{switch}$ | $P_{cond}$ | $P_{joule}$ | $P_{Fe}$ | $P_{fr,w}$ | $P_{SLL}$ |
| Flux (~V/f) | | | | + | | |
| Current (~slip) | + | + | + | | | + |
| Fundamental frequency | | | | + | + | |
| Switching frequency | + | | | - | | - |

### C. *Inverter Parameters and Control Algorithm*

Magnitude and distribution of loss components at each operating point can vary considerably according to the selected inverter and control algorithm parameters. The following considerations should therefore be taken into account. Equations (1) and (2) show the general relation between torque T, flux ψ, voltage V, frequency f and active rotor current I.

$$\psi \sim \frac{V}{f} \tag{1}$$

$$T \sim \psi . I \tag{2}$$

The magnitudes of flux and current to produce a certain amount of torque depend on the control algorithm which can be scalar V/f or vector control, open or closed loop, Field Oriented Control or Direct Torque Control. This yields that loss determining quantities (flux, current and frequency) at each operating point are a function of the applied control algorithm. Both vector and scalar control try to maintain rotor flux at a constant level over the operating range (up until the nominal voltage is reached), with vector control being able to do this under very dynamic load conditions [11]. At steady-state however, the flux differences round the nominal operating range are only minor. Considerable differences in flux and slip level do occur at low speed (low voltage), high torque points. This is due to the voltage drop across the stator resistance which decreases the rotor flux level when scalar control is applied. This effect is partly reduced if the scalar controlled inverter boosts up the voltage at low speed.

Equations (1) and (2) imply that for each operating point, an optimal balance between flux and slip (current) exists in order to minimize the total drive loss. This point is shown in Fig. 2 [12] and is given by a condition where the reduction in iron loss for a certain flux reduction equals the increase in losses due to the increasing current [13]. Modern inverters dispose of flux optimization algorithms based on an iterative search controller or a loss model of the motor drive [14].

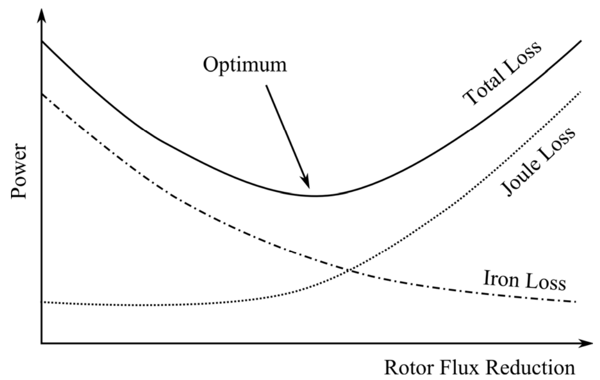


Fig. 2. Motor loss minimization with rotor flux and slip variation while maintaining constant torque.

A similar analysis can be made for the inverter's switching frequency. Faster switching yields lower harmonic content supplied to the motor resulting in lower iron and stray load losses. However, as the switches change states more often the inverter loss will increase correspondingly. In Fig. 3 an optimal switching frequency corresponding to minimal total loss can be found [15].

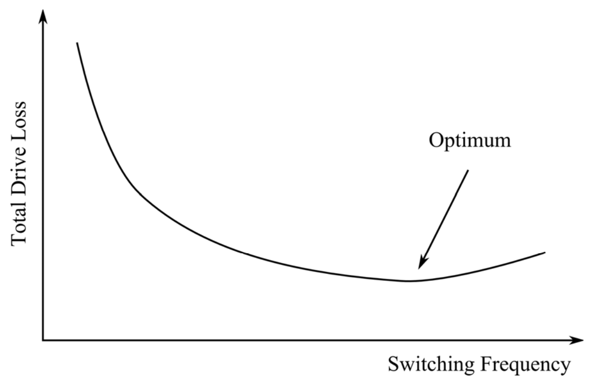


Fig. 3. Optimal switching frequency for minimal combined inverter and motor loss.

## III. Efficiency Contours

It is the intention to introduce efficiency maps, also known as iso efficiency maps or contours, as a useful tool to characterize the efficiency of VSDs. They originate from the area of vehicle applications using induction motors, switched reluctance motors or permanent magnet synchronous motors as electric traction motor. An example of such an efficiency map, recorded at the K.U. Leuven, for an induction motor drive is given in Fig. 6. Despite the fact that these maps are well incorporated and successful there, as such they are not established or even unknown in industrial applications. Nevertheless, also for the designers of VSDs in industry and other applications they have a promising potential. The maps can be used for trajectory mapping and assessment of drive or load cycles and estimation, even optimization, of the associated energy consumption. But even for less dynamic applications they could be used as a useful tool to assess where the operating point should be located in order to optimize system efficiency.

However, in order to ensure an unambiguous application of this concept for VSDs, an internationally accepted approach, i.e. a standard on efficiency contours, is required. The only wide spread and internationally accepted standards concerning motor efficiency are intended for direct-on-line use, in fact, some versions even exclude motors for traction applications [4, 8]. The work done in the context of this project is aimed to contribute to this process of international acceptation and standardization. Therefore, in the next sections, the need for standardization is discussed and elaborated more in detail. The final result of this funded discussion is the proposal of a (preliminary) measurement procedure for efficiency maps of VSDs in general (Section IV).

In fact, the IECs efficiency classification already suggests a similar approach of using efficiency maps for the efficiency limits of IE4 motors if the motors are rated for a certain speed-torque range [5, 16]. However, no specific method for the determination of the system efficiency is proposed. It is only mentioned that the direct efficiency should be measured over the motors winding connection and the mechanical output (shaft). Thus this does not take the mutual interaction between motor and converter, nor the efficiency of the converter itself into account. Even more importantly, if no extra precautions and conditions are imposed, this will not guarantee an accurate nor reproducible efficiency determination. This would be in contrast with the discussions concerning direct-on-line induction motor efficiency determination and the associated motivations for using the segregation of loss method, preferably the input-output method, over direct methods. Moreover, in recent publications introducing and promoting the new IEC efficiency classification for IMs and discussing VSD efficiency, a similar approach using a matrix of test points (pairs) for speed and torque is mentioned [16, 17]. There, a suggestion is made to limit the number of testing points according to two common application types, i.e. constant torque applications like conveyors and quadratic torque applications like pumps. But, such a low density of efficiency values does not provide sufficient information for optimal VSD choice. As explained below and clearly noticeable from the example, often the zone(s) of highest efficiency occur for lower than rated torque and slightly higher speeds. This means that if only test points around constant and quadratic torque are given, an opportunity to indicate the most desirable zone to operate the motor drive combination is missed. On the other hand, it is also important for the users of VSDs to know the operating zones which should be avoided from the point of view of energy efficiency, which is also one of the purposes of the research project presented here.

A primary requirement for unambiguous energy efficiency indication of VSDs and thus successful application of efficiency contours is that they are recorded according to a founded and internationally accepted protocol. In the next section the preconditions for and factors affecting the reproducibility and accuracy of efficiency determination of electric motors and in fact VSDs are briefly listed prior to proposing a suitable testing protocol.

For practical operating conditions, classic efficiency standards do not perfectly reflect the actual efficiency of the motor. For instance, due to the fact that also the partial load efficiency values are determined for full load stable operating temperature, the efficiency for partial load conditions is often underestimated. Such issues cannot be avoided and will also occur for VSD efficiency test protocols. Another interesting question in this context is whether efficiency maps can be used to predict the energy consumption of applications and if the quality of the estimation depends on how static or dynamic the load cycles are. The study of the energy consumption prediction for such trajectories of VSDs is described in [18].

## IV. MEASUREMENT PROCEDURE

### A. *Requirements of efficiency testing protocols*

The international accepted test protocols of IEC and IEEE for the determination of direct-on-line induction motor efficiency are composed in such a way that the results are reproducible and reasonably accurate. This should also be the main requirement of a testing protocol for VSD energy efficiency (map) determination. However, there are more degrees of freedom as scope of applications, different combination of motors, drives and control algorithm, programming or converter settings, etc. Moreover, the method of loss segregation and the (temperature) corrections as they are known from the standards IEC 60034-2-1 and IEEE 112 (method B) are not applicable as such for VSDs. All together, this demonstrates both the complexity and the necessity of a testing protocol for VSD efficiency.

### B. *Test setup and instrumentation accuracy*

Fig. 4 shows the schematic of a suitable VSD test setup. It is a facility with the capability to mechanically load the motor and drive at the different test points as determined by the test protocol. To establish this loading, a controlled dynamometer or a DC drive may be used.

The setup is also equipped with a torque and speed measurement. A digital power analyzer is used for the electrical measurements, i.e. voltage, current, frequency and computed power. The power is measured before and after the power electronic converter. The measurements are controlled in such a way that they are recorded simultaneously. The accuracy of the electrical quantities at the fundamental frequency and the torque have an accuracy of +/- 0.2%. The range of the torque transducer should be adopted to the motor and the accuracy of the speed measurement is +/- 1 rpm. However, given the nature of VSDs, harmonics at the input and output of the converter are involved and should not be ignored when selecting and programming the measurement equipment. Therefore, the frequency range of the digital power analyzer should be several kHz, preferably 200 to 300 kHz.

The test setup should also be equipped with a temperature measurement device to keep track of the motor temperature. This temperature sensor should be located as near to the stator winding as possible, preferably in a slot or on the end-windings.

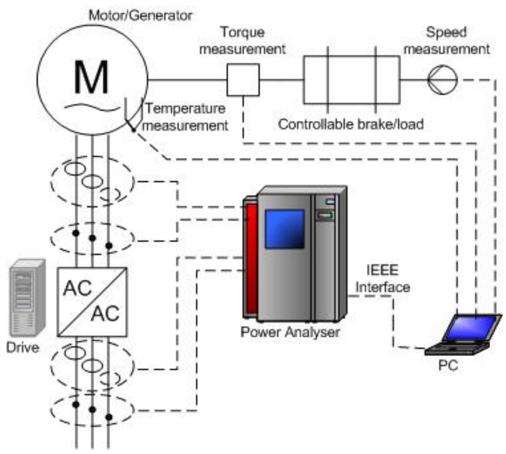


Fig. 4: Schematic of VSD test setup.

### C. *Testing protocol*

As already mentioned, the segregation of loss method and the linked (temperature) corrections are not easily applicable. Therefore, the direct method for the determination of motor, drive and total efficiency is used. Consequently, this makes the precautions described in the instrumentation requirements and in the test protocol proposed below increasingly important as they are the main tools to approximate reproducible results.

1) Make sure that the bearings are well ran in.
2) Use a test setup and instrumentation with specifications according to the description above.
3) It is recommended to also determine the direct-on-line efficiency according to IEEE or IEC standards.
4) The ambient temperature during the test must be between 20 and 25$^0$C.
5) Determine the rated operating temperature by running the VSD at rated conditions until the temperature does not change more than 1$^0$C within 30 minutes. Choose this temperature or a temperature slightly lower as test temperature.
6) For a chosen matrix of test points [19], the measurements are performed. Preferably, start with choosing a (nearly) fixed speed and ‘scan’ the preferred load points starting with the highest torque until the lowest partial load point. Make sure that the motor temperature stays within +/- 5$^0$C of the test temperature.
   a) Before recording each point, make sure that a stable operating point is reached.
   b) If possible record several points for averaging during post processing. Make sure that the settings on the power analyzer are correct.
   c) If motor temperature exceeds the limits, higher or lower the loading and/or speed until the test temperature is reached again and retake the entire set of load points .
   d) The sequence of speed ranges may be chosen such that there is a good mix of good and bad cooling conditions, i.e. high and low speeds if the fan is shaft mounted.
7) If desired repeat tests for generator mode.
8) Regularly check and take into account the offsets of the torque transducer.

Remark that if required, interpolation between measurement sets is possible. More information on the choice of the test matrix, required density of test points and accuracy linked with such interpolations can be found in [19].

## V. Example

In order to illustrate the previously discussed concept and measurement procedure with an example, Fig. 5, Fig. 6 and Fig. 7 present iso efficiency contours of a VSD that was tested at the K.U. Leuven ELECTA laboratory. The 11 kW 4-pole induction motor is being fed by a scalar controlled inverter. The particular shape of the contours is a direct consequence of the change in magnitude of loss components over the operating range caused by a variation in frequency, flux and current (slip) as indicated in Table I. Two regions can be distinguished; the constant flux and the field weakening region. The blue line indicates nominal torque and power operation respectively under and above nominal frequency.

Fig. 8 gives a strongly approximated evolution of motor and inverter loss components in the constant flux and field weakening region. Low speed - high torque points have very low efficiency due to output power independent losses. As speed increases, the efficiency improves rapidly (small spacing between contours) reaching an optimum around synchronous speed. At nominal power operation in the flux weakening region, iron losses become approximately constant, the friction and windage losses gain in amplitude and the lower magnetizing current yields a reduction of joule loss. This causes a difference in slope between the nominal power line and the efficiency contours in Fig. 5 and 6. Notice that the efficiency would remain practically constant if the change in $P_{fr,w}$ and $P_{joule}$ could be neglected.

It appears that highest motor efficiency occurs at points of lower torque and slightly higher speed than rated [7]. Because a lower torque yields less slip (lower current), it leads to a reduction in joule losses proportional to the torque reduction squared.

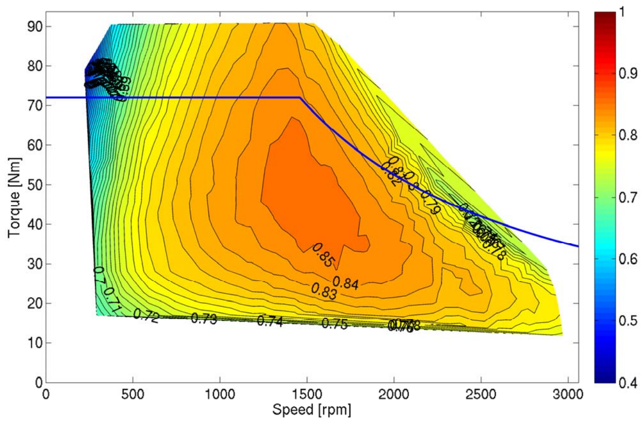


Fig. 5. Combined motor and inverter iso efficiency contours.

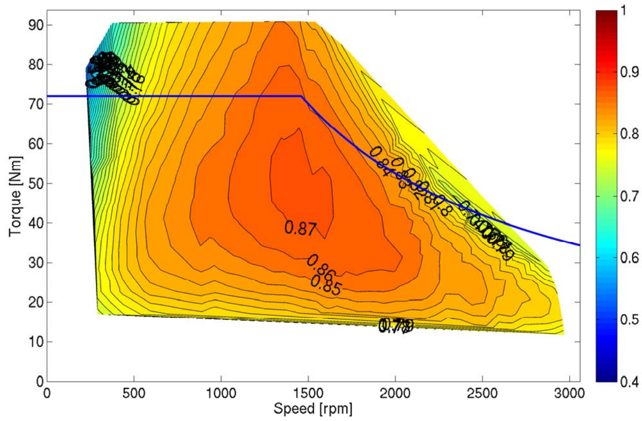


Fig. 6. Motor iso efficiency contours.

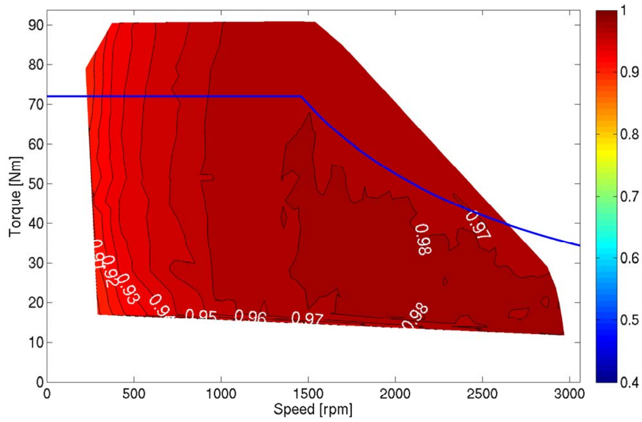


Fig. 7. Inverter iso efficiency contours.

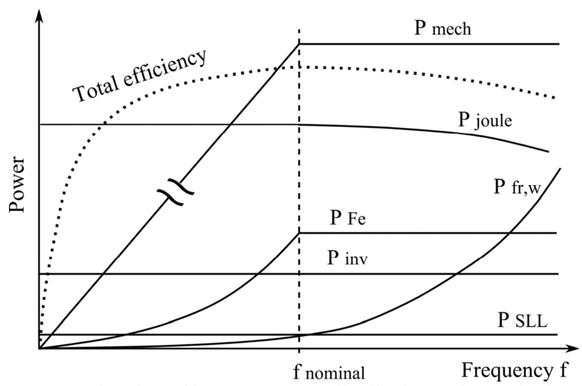


Fig. 8. Approximation of loss component distribution and magnitude under constant torque (f<50Hz) and constant power (f>50Hz) operation.

## VI. Conclusion

To date, there is no internationally accepted standard for efficiency determination of variable speed drives at different load points. The discussion about this lacuna and how to provide a solution is ongoing. In this paper, the concept of iso efficiency contours together with a brief description of a test-bench and a preliminary test-procedure is put forward as a contribution to the discussion. The biggest problem however is the reproducibility of measurements as the direct input-output method has to be used. The influence of temperature is reduced by imposing ambient temperature and motor temperature deviation limits. Measurement errors however cannot be cancelled out as it is the case with indirect methods. The attainable reproducibility of the proposed method and how to enhance it is an item for future research. The concept of iso efficiency contours and the measurement procedure has proven its potential throughout an extensive measurement campaign in cooperation with industrial partners. An example is presented together with a first analysis and interpretation of the contour shapes.

## VII. Acknowledgement

The research described in this paper is a result of a fruitful collaboration [17, 18] between three research institutes: FMTC, ELECTA and Howest. Special thanks goes out to Roland Reekmans for the practical realization of the test setup and his expertise during the measurement campaign.

## VIII. References


[1] "www.ecomotors.org, last accessed on 21/01/2010."

[2] A. T. de Almeida, F. J. T. E. Ferreira, P. Fonseca, B. Chretien, H. Falkner, J. C. C. Reichert, M. West, S. B. Nielsen, and D. Both, "VSDs for Electric Motor Systems," European Commission: The Motor Challenge Programme, ISR-University of Coimbra, publication available at http://sunbird.jrc.it/energyefficiency/motorchallenge/pdf/VSDs-SAVE-Study-Final-Report.pdf, last verified Oct. 2008.

[3] H. De Keulenaer, R. Belmans, E. Blaustein, and e. al., *Energy Efficient Motor Driven Systems. Can Save Europe 200 Billion kWh of Electricity Consumption and over 100 Million Tonnes of Greenhouse gas Emissions a Year*. Brussels, Belgium: European Copper Institute, 2004.

[4] "Rotating electrical machines - Part 2, Ed. 4: Methods for determining losses and efficiency from tests (excluding machines for traction vehicles)," *IEC Standard 60034-2 Ed. 4,* 2007.

[5] "Rotating electrical machines - Part 30: Efficiency classes of single-speed, three-phase, cage-induction motors (IE-code)," *IEC Standard 60034-30, (2008 - 10),* 2008.

[6] "Rotating electrical machines - Part 31: Guide for the selection and application of energy-efficient motors including variable-speed applications," *IEC Standard 60034-31 Committee Draft,* 2009.

[7] S. S. Williamson, S. M. Lukic, and A. Emadi, "Comprehensive Drive Train Efficiency Analysis of Hybrid Electric and Fuel Cell Vehicles Based on Motor-Controller Efficiency Modeling," *IEEE Transactions on Power Electronics,* vol. 21, pp. 730-740, 2006.

[8] "IEEE Standard Test Procedure for Polyphase Induction Motors and Generators," *IEEE Std 112-2004 (Revision of IEEE Std 112-1996),* pp. 0_1-79, 2004.

[9] M. H. Bierhoff and F. W. Fuchs, "Semiconductor losses in voltage source and current source IGBT converters based on analytical derivation," in *Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual*, 2004, pp. 2836-2842 Vol.4.

[10] W. Deprez, "Energy efficiency of induction machines: a critical assessment," 2008, p. 217.

[11] J. W. Finch, "Scalar and vector: a simplified treatment of induction motor control performance," in *Vector Control Revisited (Digest No. 1998/199), IEE Colloquium on*, 1998, pp. 2/1-2/4.

[12] E. M. Tsambouris and A. G. Kladas, "Efficiency optimization considerations for standard induction motor fed by PWM inverter," in *Advanced Electromechanical Motion Systems & Electric Drives Joint Symposium, 2009. ELECTROMOTION 2009. 8th International Symposium on*, 2009, pp. 1-6.

[13] F. Abrahamsen, F. Blaabjerg, J. K. Pedersen, and P. B. Thoegersen, "Efficiency-optimized control of medium-size induction motor drives," *Industry Applications, IEEE Transactions on,* vol. 37, pp. 1761-1767, 2001.

[14] M. N. Uddin and N. Sang Woo, "New Online Loss-Minimization-Based Control of an Induction Motor Drive," *Power Electronics, IEEE Transactions on,* vol. 23, pp. 926-933, 2008.

[15] T. Marcic, G. Stumberger, M. Hadziselimovic, and I. Zagradisnik, "Analysis of Induction Motor Drive Losses in the Field-Weakening Region," in *Power Electronics and Motion Control Conference, 2006. EPE-PEMC 2006. 12th International*, 2006, pp. 1173-1178.

[16] M. Doppelbauer, "Guide for the Selection and Application of Energy-efficient Motors," in *EEMODS '09: Energy Efficiency in Motor Driven Systems* Nantes, France, 2009.

[17] A. I. de Almeida, C. U. Brunner, P. Angers, and M. Doppelbauer, "Motors with Adjustable Speed Drives: Testing Protocol and Efficiency Standard," in *EEMODS '09: Energy Efficiency in Motor Driven Systems* Nantes, France, 2009.

[18] D. Vanhooydonck, W. Symens, W. Deprez, J. Lemmens, K. Stockman, and S. Dereyne, "Calculating Energy Consumption of Motor Systems with Varying Load using Iso Efficiency Contours," in *submitted for ICEM 2010, International Conference on Electrical Machines* Rome, Italy, 2010.

[19] K. Stockman, S. Dereyne, D. Vanhooydonck, W. Symens, J. Lemmens, and W. Deprez, "Iso Efficiency Contour Measurement Results for Variable Speed Drives," in *submitted for ICEM 2010, International Conference on Electrical Machines* Rome, Italy, 2010.


## IX. Biographies

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**Dirk Vanhooydonck** received the M.Sc. degree in mechanical engineering, option mechatronics (1999) and the Ph.D. in applied sciences, focusing on robotics (2007), both from the Katholieke Universiteit Leuven. Currently he is involved at the Flanders' Mechatronics Technology Centre (FMTC) in projects dealing with energy efficiency of high-productivity machines.

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